AFRL-RX-WP-TP-2008-4313

EXPERIMENTAL EJECTION FORCES OF THERMOPLASTIC PARTS FROM RAPID TOOLED INJECTION MOLD INSERTS (PREPRINT)

Mary E. Kinsella and Blaine Lilly

Metals Branch
Metals, Ceramics, and NDE Division

JUNE 2007

Approved for public release; distribution unlimited.
See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 2007	Journal Article Preprint	

4. TITLE AND SUBTITLE
EXPERIMENTAL EJECTION FORCES OF THERMOPLASTIC PARTS FROM RAPID TOOLED INJECTION MOLD INSERTS (PREPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62102F

6. AUTHOR(S)
Mary E. Kinsella (AFRL/RXLMP)
Blaine Lilly (The Ohio State University)

5d. PROJECT NUMBER
4347

5e. TASK NUMBER
RG

5f. WORK UNIT NUMBER
M02R2000

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Metals Branch (AFRL/RXLMP)
Metals, Ceramics, and NDE Division
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command, United States Air Force

The Ohio State University

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RX-WP-TP-2008-4313

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RXLMP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RX-WP-TP-2008-4313

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Journal article submitted to *Rapid Prototyping Journal.*

PAO Case Number: MLLM-0028; Clearance Date: 24 May 2007. The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work. Paper contains color.

14. ABSTRACT
The application of rapid prototyped tools for injection molding, if technically feasible, may allow for small quantity production by reducing the cost of tooling. This work has investigated one aspect of the technical feasibility through testing and experimentation to determine ejection force requirements and coefficients of friction. Injection molding experiments were conducted using three mold insert materials, P-20 steel, laser sintered ST-100, and stereolithography SL 5170 resin. Ejection forces for cylindrical parts molded with high density polyethylene and high impact polystyrene were measured directly and compared with values calculated from an ejection force differently, depending on the materials characteristics. Results show that ST-100 is a good candidate for injection molding tools, and that SL 5170 might be a candidate for molding some thermoplastics, but only in very small quantities.

15. SUBJECT TERMS
injection molding, ejection force, coefficients of friction, P-20 steel, laser sintered ST-100, SL 5170 resin, thermoplastic

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	22	Sheldon L. Semiatin
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Experimental Ejection Forces of Thermoplastic Parts from Rapid Tooled Injection Mold Inserts

Mary E. Kinsella, Materials and Manufacturing Directorate, Air Force Research Laboratory
Blaine Lilly, Industrial and Systems Engineering, The Ohio State University

Abstract

The application of rapid prototyped tools for injection molding, if technically feasible, may allow for small quantity production by reducing the cost of tooling. This work has investigated one aspect of the technical feasibility through testing and experimentation to determine ejection force requirements and coefficients of friction. Injection molding experiments were conducted using three mold insert materials, P-20 steel, laser sintered ST-100, and stereolithography SL 5170 resin. Ejection forces for cylindrical parts molded with high density polyethylene and high impact polystyrene were measured directly and compared with values calculated from an ejection force model. Process parameters affected the friction and shrinkage components of ejection force differently, depending on the materials characteristics. Results show that ST-100 is a good candidate for injection molding tools, and that SL 5170 might be a candidate for molding some thermoplastics, but only in very small quantities.

Introduction

Thermoplastic injection molding is typically used for high volumes of products because injection molds are expensive, regardless of part size, and require many parts over which to amortize their costs. In small volume production environments, the cost of tooling must be low to keep the products affordable. Rapid tooling is one approach that has the potential to reduce tooling costs and enable the production of small quantities of injection molded products. Rapid tooling encompasses many processes based on the rapid prototyping concepts of additive, layer-by-layer manufacturing, such as stereolithography and laser sintering. An insert for a modular injection mold can be made using rapid tooling techniques. The insert contains the geometry of the part to be injection molded and can be interchangeable or even disposable.

The advantages of using rapid tooling techniques to build an insert are 1) the insert is built directly from a CAD file using an efficient layer-by-layer process; 2) the design can be iterated more efficiently than with conventional machined steel inserts; and 3) complex part geometries and conformal cooling lines can be incorporated. A disadvantage is that the material properties of rapid tooled injection mold inserts, especially those of nonmetal materials, do not often compare to those of traditional machined steel inserts. For example tensile strength and conductivity are often much lower in rapid tooled inserts compared to machined steel inserts. Material properties of some rapid tools may, however, be adequate to meet some small quantity injection molded part requirements since the number of thermal and mechanical cycles may be reduced and because cycle time requirements may not be as stringent.

This research addressed the suitability of rapid tooled injection mold inserts for small quantity injection molding. The scope was limited to aspects related to ejection force, or the force on the core of a mold resulting from ejection of the molded part from it. An experimental approach was taken to determine the ejection forces that rapid tooled injection mold inserts would be required to withstand, how they compare among different insert materials, and what process parameters affect them. The experimental ejection forces were also compared to those from a model. Based on experimental results, a general assessment is given of the ability of rapid tooled injection mold inserts to produce quality parts [1].

Background

The injection mold used for this work is shown in exploded view in Figure 1. The mold bases, housings and stripper plate were made of steel. One injection mold insert consists of two parts: a core and a cavity. Three different core and cavity insert pairs were built for this experimental research. The first was a traditionally machined P-20 steel insert used as a baseline. The second was a Laserform ST-100 insert made of stainless steel and bronze using a laser sintering rapid manufacturing process. The third was a SL 5170 insert made of a resin material using a stereolithography rapid manufacturing process. Each insert was machined to fit into the modular mold base. Core surface finishes were Ra = 0.7 microinches for the P-20 steel and SL 5170 inserts, and Ra = 0.3 microinches for the Laserform ST-100 insert. The inserts are shown in Figure 2, descriptions of the inserts are summarized in Table 1, and cavity and core assemblies are shown in Figure 3. Properties of the two rapid tooling materials, according to the equipment manufacturers, are found at [2] and [3].

The injection mold inserts described above were designed to produce a small thermoplastic canister part: a closed-end, straight cylinder having 32 mm (1.26 in) outside diameter, 49.6 mm (1.95 in) height, 1.2 mm (0.05 in) wall thickness, and four vent holes in the base. Two thermoplastic materials were used to mold the cylindrical part, high density polyethylene (HDPE) and high impact polystyrene (HIPS). These materials represent two commonly used materials in the injection molding industry. The HDPE is considered to be a crystalline polymer, and the HIPS is an amorphous polymer. The cylindrical part is shown in Figure 4, and descriptions of the thermoplastic materials are shown in Table 2.

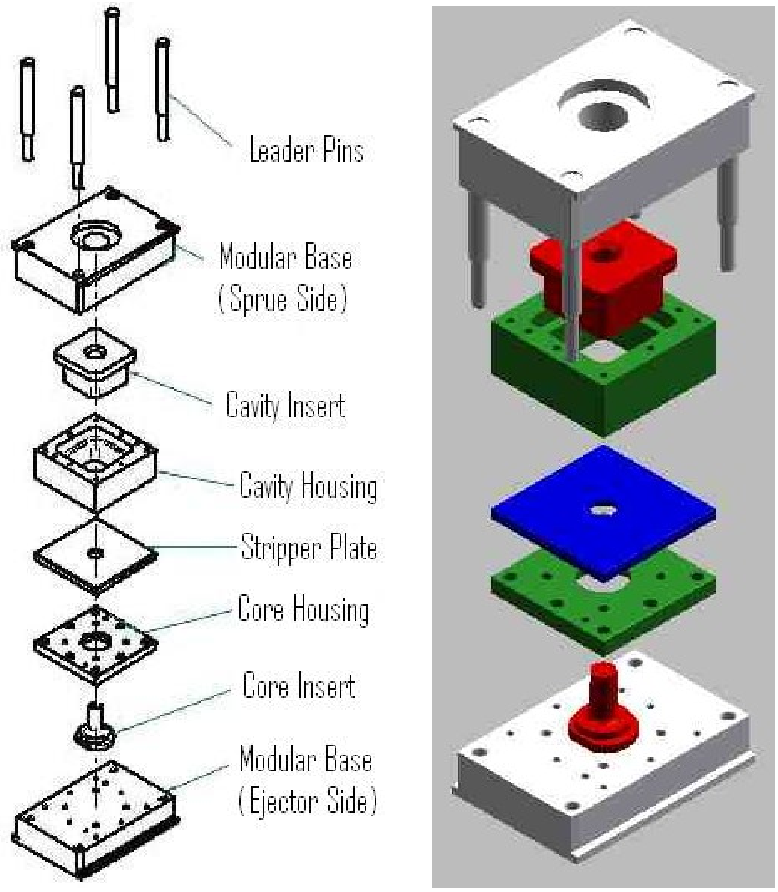


Figure 1: Exploded views of the injection mold used for this research.

Figure 2: Insert cores and cavities before final machining: SL5170 (left), P-20 steel (center), and ST-100 (right).

Mold Inserts	Material	Description
Conventional:	P-20	Machined steel (baseline)
Rapid Tools:	Laserform ST-100	Laser sintered stainless steel powder infiltrated with bronze
	SL 5170	Stereolithography epoxy-based resin

Table 1: Description of the three injection mold inserts used in the experiments.

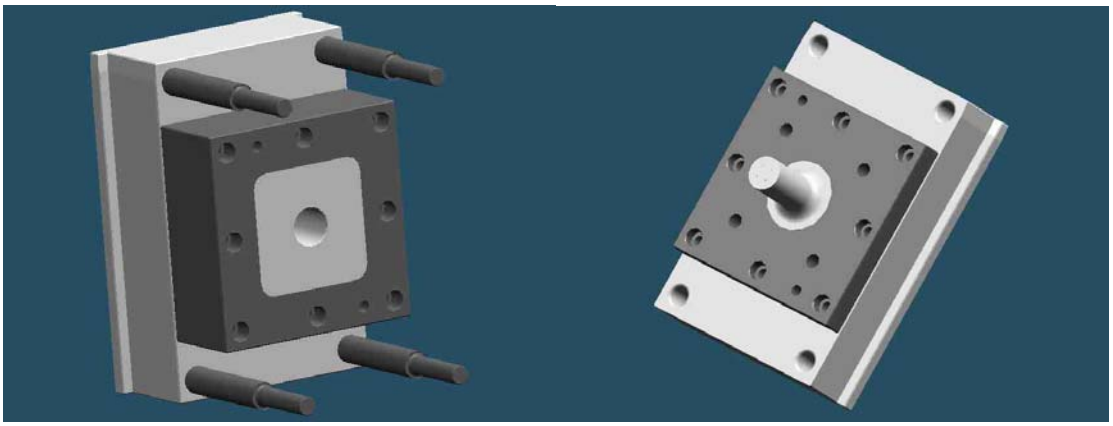


Figure 3: Cavity (left) and core (right) assembly portions of the injection mold.

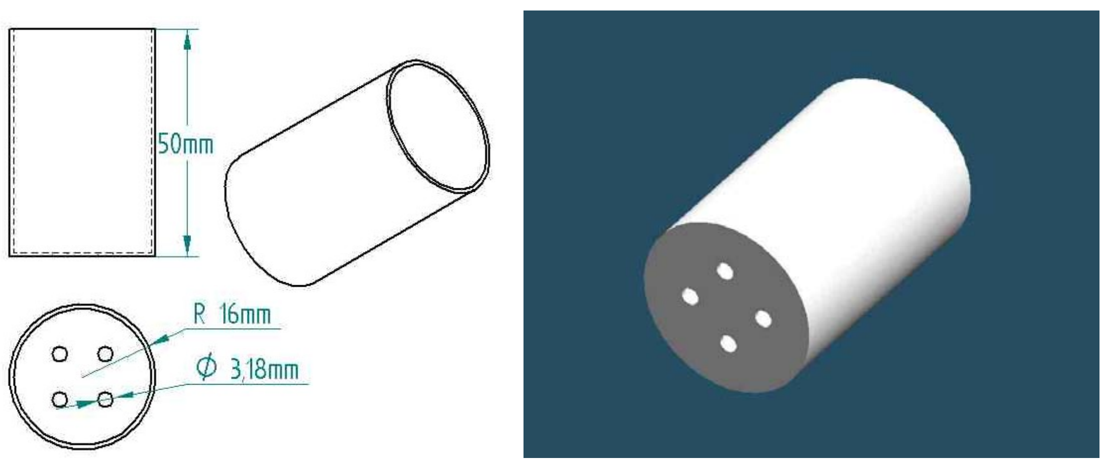


Figure 4: The cylindrical part produced by the injection mold and inserts during experimentation.

Thermoplastic Material	Description	Manufacturer	Melt/Glass Transition Temperature
High Density Polyethylene (HDPE)	Lutene-H ME9180	LG Chem	Tm = 133C (271F)
High Impact Polystyrene (HIPS)	BASF PS 495F	BASF	Tg = 100C (212F)

Table 2: Thermoplastic materials used to mold the cylindrical part during experimentation.

Ejection Force

Two important aspects of ejection force are shrinkage and friction. Shrinkage influences the contact pressure of the part on the injection mold core. The extent of shrinkage that occurs depends on material properties and process conditions. Furthermore the effects of cooling time, packing pressure, and packing time on ejection force are determined in part by the shrinkage characteristics of the thermoplastic material. Friction between the thermoplastic part and the injection mold core not only depends on the mechanical relationship between the two surfaces, but also on an adhesive component inherent in the properties of the two materials at processing conditions. In this work, adhesion was found to be high between HIPS and SL 5170 resin [4][5][6].

Several researchers have developed force equations for the ejection of parts from injection mold cores based on mechanical or thermo-mechanical models, [7][8][9][10]. Ejection force equations are derived from the empirical law of the friction phenomenon, in which the friction force between two surfaces is proportional to the normal force pressing the two surfaces together:

$$F = \mu N \qquad (1)$$

where N is the normal force and μ is the coefficient of friction, a characteristic constant of the materials involved.

For deep injection molded parts produced with cores and cavities, the friction force is equal to the release force F_R, and the normal force results from the product of the contact pressure P and the area of contact A:

$$F_R = \mu P A \qquad (2)$$

The stresses in an injection molded cylindrical part before ejection can be modeled as stresses in a thin-walled cylindrical pressure vessel, i.e., hoop stress σ_1 is

$$\sigma_1 = \frac{pr}{t} \qquad (3)$$

Where p is the contact pressure, r is the radius of the core and t is the wall thickness.

Using Hooke's Law and given that strain can be represented by thermal strain, the stress can be written as

$$\sigma = E(T)\alpha(T_M - T_E) \quad 4$$

Combining the previous three equations and given that the area of the cylinder $A = \pi D_c L$ results in a model for release force as follows

$$F_R = \frac{\mu E(T)\alpha(T_M - T_E)t\pi D_c L}{r_c} \quad 5$$

Strain may be approximated by the relative change in diameter Δd_r of the cylinder immediately after ejection [9]. With this change, then, the ejection force is:

$$F_R = \frac{\mu E(T)\Delta d_r t\pi D_c L}{r_c} \quad 6$$

Experimentation

Prior to the injection molding experiments, tests were conducted to measure elastic moduli and friction coefficients of the thermoplastic part materials. Elastic moduli for the HDPE and HIPS materials were measured at various temperatures using ASTM D 638. The coefficients of static friction of HDPE and HIPS were measured against P-20 mold steel, LaserForm ST-100, and SL 5170 stereolithography resin following ASTM D 1894. All of the materials tested were identical to those used in the injection molding experiments. Modulus results are shown in Figure 5, and friction test results can be found in [11].

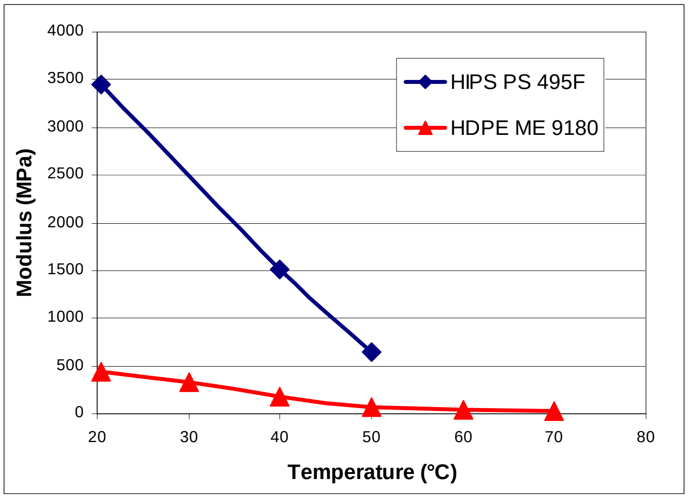


Figure 5: Elastic modulus at various temperatures for HDPE and HIPS.

All injection molding experiments were performed on a 50-ton hydraulic, horizontal press. Barrel zone temperatures were set based on commonly used temperatures for injection molding HDPE and HIPS. Machine parameters are shown in Table 3. The velocity and temperature parameters for each set of experiments are shown in Table 4. Three parameters were varied in each experiment: packing time, cooling time, and packing pressure. The levels of these parameters for the designed experiment are shown in Table 5.

Since the SL 5170 insert was expected to be less durable, temperature and velocity settings were reduced as far as possible without compromising mold fill. The number of experimental runs was reduced by reducing the number of cooling time and packing pressure parameter levels from two to one (Table 5). Cooling times were increased to 120 and 150 seconds to allow for the low thermal conductivity of the stereolithography resin.

There were a total of six experimental sets. Each experimental set was blocked by insert material and thermoplastic part material, and randomized by packing time (Tp), cooling time (Tc), and packing pressure (Pp). The full experimental design is shown in Table 6.

Only a limited number of parts could be processed using the SL 5170 cavity due to deformation that caused sticking of parts. The last two sets of the designed experiment, therefore, were carried out using the SL 5170 core with the P-20 cavity. The steel cavity material significantly changed the thermal performance of this insert and reduced the temperature at ejection, but also allowed a complete experiment to be performed in which ejection force from the SL 5170 core could be measured.

Sumitomo horizontal press, 50-ton, hydraulic
25% maximum screw rpm
5% maximum back pressure
15% maximum ejection velocity
20 metric ton clamping force

Table 3: Injection molding machine parameters used during experiments.

HDPE with P-20 Steel and LaserForm ST-100 Inserts
Velocity: 35% or 56 mm/s (2.2 in/s)

Temperature Profile:	Sprue	Nozzle	Front	Middle	Rear
	210^oC	210^oC	199^oC	193^oC	177^oC

HIPS with P-20 Steel and LaserForm ST-100 Inserts
Velocity: 40% or 64 mm/s (2.5 in/s) for P-20, 35% or 56 mm/s (2.2 in/s) for ST-100

Temperature Profile:	Sprue	Nozzle	Front	Middle	Rear
	221^oC	221^oC	213^oC	204^oC	191^oC

HDPE with SL 5170 Insert, SL or P-20 Cavity
Velocity: 25% or 40 mm/s (1.6 in/s)

Temperature Profile:	Sprue	Nozzle	Front	Middle	Rear
	177^oC	177^oC	171^oC	166^oC	160^oC

HIPS with SL 5170 Insert, SL or P-20 Cavity
Velocity: 40% or 64 mm/s (2.5 in/s)

Temperature Profile:	Sprue	Nozzle	Front	Middle	Rear
	210^oC	216^oC	202^oC	193^oC	182^oC

Table 4: Injection velocity and temperature parameters for each material combination.

Statistical Design of Experiments

Inputs:	Levels for P-20 and ST-100 inserts			Levels for SL 5170 insert	
	Low	Med	High	Low	High
Packing Time (Tp)	2 sec	--	6 sec	2 sec	6 sec
Cooling Time (Tc)	5 sec	10 sec	15 sec	120 sec	150 sec
Packing Pressure (Pp)	0%	5%	10%	0%	5%
	0 MPA	11 MPA	22 MPA	0 MPA	11 MPA

Table 5: Experimental design inputs with levels defined for each mold insert material.

SET 1	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
P-20	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s
HDPE	Tc = 15 s	Tc = 5 s	Tc = 15 s	Tc = 15 s	Tc = 10 s	Tc = 5 s	Tc = 5 s	Tc = 10 s	Tc = 10 s
8 Reps	Pp = 0%	Pp = 10%	Pp = 10%	Pp = 5%	Pp = 10%	Pp = 5%	Pp = 0%	Pp = 0%	Pp = 5%
	Run 10	**Run 11**	**Run 12**	**Run 13**	**Run 14**	**Run 15**	**Run 16**	**Run 17**	**Run 18**
	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s
	Tc = 15 s	Tc = 5 s	Tc = 5 s	Tc = 15 s	Tc = 10 s	Tc = 10 s	Tc = 15 s	Tc = 5 s	Tc = 10 s
	Pp = 10%	Pp = 0%	Pp = 5%	Pp = 5%	Pp = 0%	Pp = 5%	Pp = 0%	Pp = 10%	Pp = 10%

SET 2	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
P-20	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s
HIPS	Tc = 15 s	Tc = 5 s	Tc = 15 s	Tc = 15 s	Tc = 10 s	Tc = 5 s	Tc = 5 s	Tc = 10 s	Tc = 10 s
8 Reps	Pp = 0%	Pp = 10%	Pp = 10%	Pp = 5%	Pp = 10%	Pp = 5%	Pp = 0%	Pp = 0%	Pp = 5%
	Run 10	**Run 11**	**Run 12**	**Run 13**	**Run 14**	**Run 15**	**Run 16**	**Run 17**	**Run 18**
	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s
	Tc = 15 s	Tc = 5 s	Tc = 5 s	Tc = 15 s	Tc = 10 s	Tc = 10 s	Tc = 15 s	Tc = 5 s	Tc = 10 s
	Pp = 10%	Pp = 0%	Pp = 5%	Pp = 5%	Pp = 0%	Pp = 5%	Pp = 0%	Pp = 10%	Pp = 10%

SET 3	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
ST-100	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s
HDPE	Tc = 15 s	Tc = 5 s	Tc = 15 s	Tc = 15 s	Tc = 10 s	Tc = 5 s	Tc = 5 s	Tc = 10 s	Tc = 10 s
8 Reps	Pp = 0%	Pp = 10%	Pp = 10%	Pp = 5%	Pp = 10%	Pp = 5%	Pp = 0%	Pp = 0%	Pp = 5%
	Run 10	**Run 11**	**Run 12**	**Run 13**	**Run 14**	**Run 15**	**Run 16**	**Run 17**	**Run 18**
	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s
	Tc = 15 s	Tc = 5 s	Tc = 5 s	Tc = 15 s	Tc = 10 s	Tc = 10 s	Tc = 15 s	Tc = 5 s	Tc = 10 s
	Pp = 10%	Pp = 0%	Pp = 5%	Pp = 5%	Pp = 0%	Pp = 5%	Pp = 0%	Pp = 10%	Pp = 10%

SET 4	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
ST-100	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s	Tp = 2 s
HIPS	Tc = 15 s	Tc = 5 s	Tc = 15 s	Tc = 15 s	Tc = 10 s	Tc = 5 s	Tc = 5 s	Tc = 10 s	Tc = 10 s
8 Reps	Pp = 0%	Pp = 10%	Pp = 10%	Pp = 5%	Pp = 10%	Pp = 5%	Pp = 0%	Pp = 0%	Pp = 5%
	Run 10	**Run 11**	**Run 12**	**Run 13**	**Run 14**	**Run 15**	**Run 16**	**Run 17**	**Run 18**
	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s	Tp = 6 s
	Tc = 15 s	Tc = 5 s	Tc = 5 s	Tc = 15 s	Tc = 10 s	Tc = 10 s	Tc = 15 s	Tc = 5 s	Tc = 10 s
	Pp = 10%	Pp = 0%	Pp = 5%	Pp = 5%	Pp = 0%	Pp = 5%	Pp = 0%	Pp = 10%	Pp = 10%

SET 5	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
SL 5170	Tp = 2 s	Tp = 2s	Tp = 6 s	Tp = 6 s	Tp = 2s	Tp = 2s	Tp = 6 s	Tp = 6 s
HDPE	Tc = 150s	Tc = 120s	Tc = 150s	Tc = 120s	Tc = 150s	Tc = 120s	Tc = 150s	Tc = 120s
5 Reps	Pp = 0%	Pp = 0%	Pp = 0%	Pp = 0%	Pp = 5%	Pp = 5%	Pp = 5%	Pp = 5%

SET 6	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
SL 5170	Tp = 2 s	Tp = 2s	Tp = 6 s	Tp = 6 s	Tp = 2s	Tp = 2s	Tp = 6 s	Tp = 6 s
HIPS	Tc = 150s	Tc = 120s	Tc = 150s	Tc = 120s	Tc = 150s	Tc = 120s	Tc = 150s	Tc = 120s
5 Reps	Pp = 0%	Pp = 0%	Pp = 0%	Pp = 0%	Pp = 5%	Pp = 5%	Pp = 5%	Pp = 5%

Table 6: Experimental matrix showing insert material, injection material, packing time Tp, cooling time Tc, packing pressure Pp, and number of repetitions for each run.

For each experimental part, ejection force, core temperature, and part diameter were measured. Ejection force data were used to determine the initial force required to release each part from the core. Thermal data were used to determine the elastic modulus of each thermoplastic part material at ejection. Inside and outside diameters of the canister parts were used to determine part thickness at ejection. All of these data were used with the ejection force model to calculate a value for the ejection force.

Temperature data were collected via three thermocouples in each core (Figure 6), and ejection force data were collected via four subminiature load cells located behind four ejector pins coupled to the stripper plate. Sample traces of core temperature and ejection force are shown in Figure 7. Digital imaging was used to measure the part diameters.

Visual inspection was used to verify that each part was of acceptable quality. If the parts did not contain any flaws, such as short shots, flashing, or bubbles, then they were determined to be acceptable. Each insert was considered to have a successful injection if it produced a quality part.

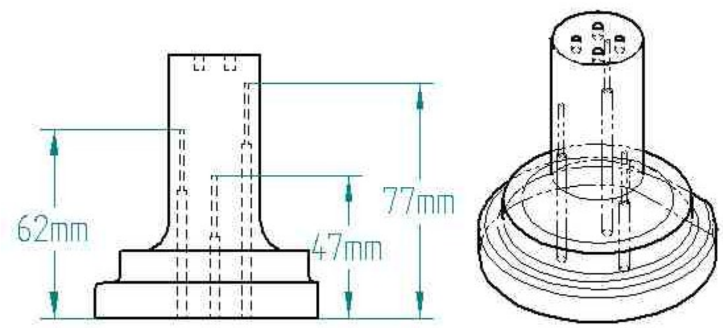
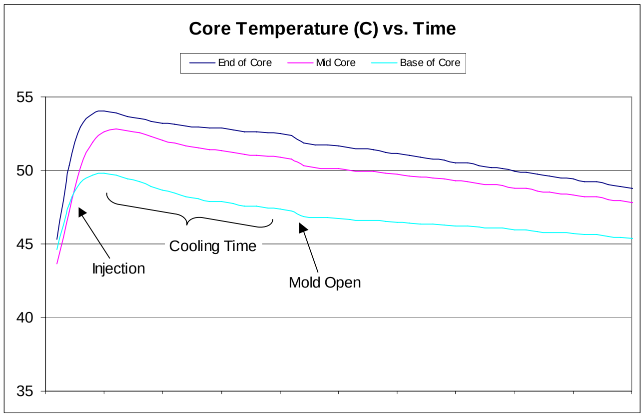


Figure 6: Thermocouple placement within the core insert.



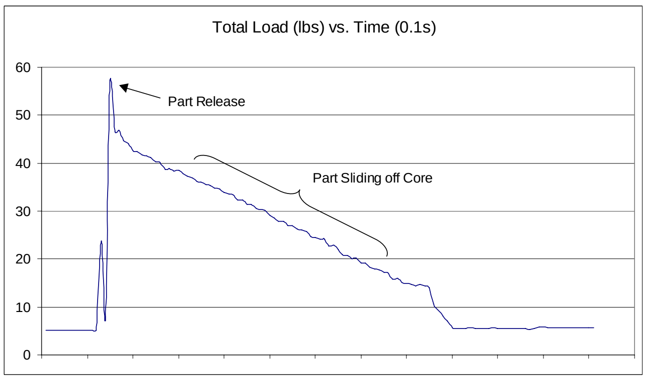


Figure 7: Representative thermal (upper) and ejection force (lower) traces.

Results and Conclusions

Ejection force results are shown by injection mold insert material in Figures 8 and 9. Analysis of variance results, indicating which parameter variables had an effect on ejection force, are shown in Table 7. Possible sources of error are shown in Table 8. Calculated values for ejection force, averaged across all runs, are compared with experimental values for all inserts in Figure 10 (HDPE) and Figure 11 (HIPS). The calculated values were determined using the measured values for coefficient of static friction at elevated temperature [11] and the model derived above.

Figure 8 shows that ejection forces for parts from the ST-100 core were generally similar to those from the P-20 baseline core. From either of these two metal cores, ejection forces for HDPE parts were lower than the ejection forces for HIPS parts. This is generally due to greater stiffness of the HIPS material.

Figure 9 shows that HDPE parts from the SL 5170 core and cavity had lower ejection forces than those from the SL 5170 core with the P-20 cavity, and, conversely, HIPS parts from the SL 5170 core and cavity had higher ejection forces than those from the SL 5170 core with the P-20 cavity. The SL 5170 core with the P-20 cavity exhibited lower ejection temperatures than the SL 5170 core and cavity due to greater thermal conductivity in the P-20 material. This lower ejection temperature had a different effect on the HDPE parts compared to the HIPS parts. For HDPE parts, lower ejection temperature had the effect of increasing shrinkage and increasing ejection force. Whereas, for HIPS parts, lower ejection temperature had the effect of reducing adhesion and reducing ejection force.

Table 7 shows that packing time had an effect on both thermoplastics with both rapid tooled inserts, and on HIPS for all three inserts. Cooling time had an effect on both thermoplastics with the P-20 insert, and on HDPE only with the ST-100 insert. All three factors had an effect on HIPS with the P-20 mold insert. In the case of the baseline P-20 insert, effects are very different between the two thermoplastic materials. For the two rapid tooled inserts, there is not as much difference in effects between the two thermoplastic materials.

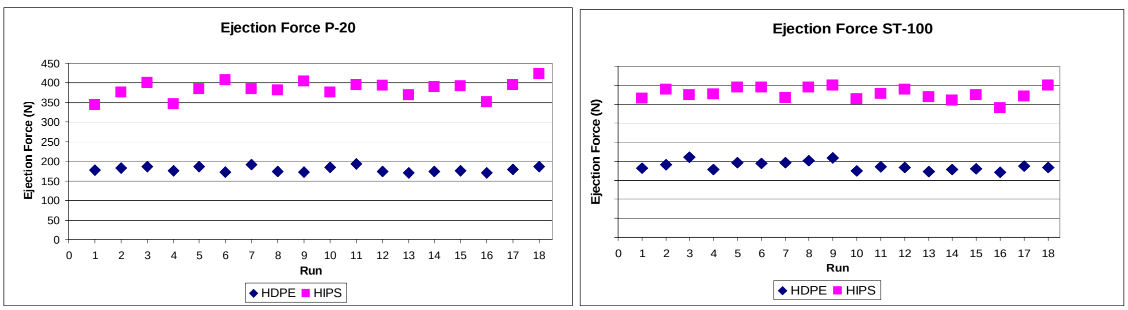


Figure 8: Experimental ejection force results from the P-20 and ST-100 inserts.

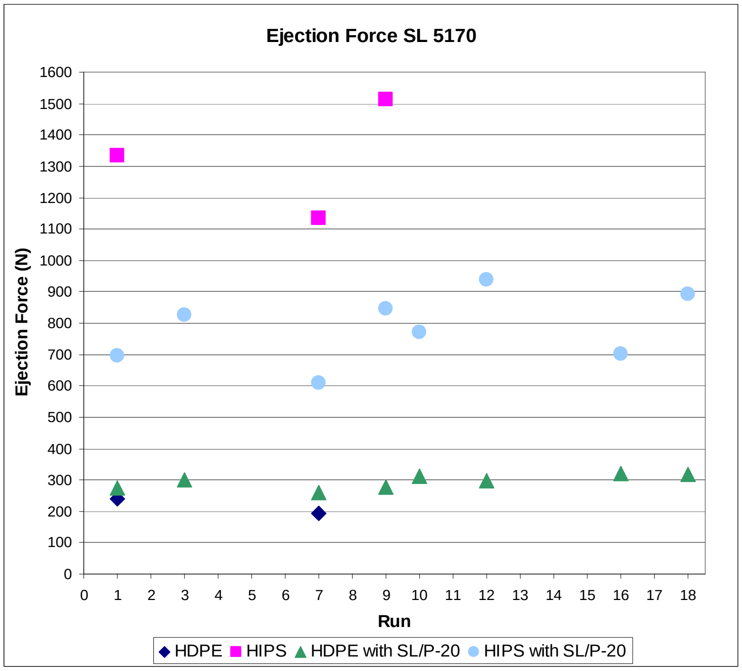


Figure 9: Experimental ejection force results from the SL 5170 insert and the combination SL 5170/P-20 insert (all completed runs are shown).

		Main Effects on Ejection Force			Interactions			
	Insert Material	Packing Time Tp	Cooling Time Tc	Packing Pressure Pp	Tp-Tc	Tp-Pp	Tc-Pp	Tp-Tc-Pp
HDPE	P-20 Steel		✔					✔
	Sintered ST-100	✔	✔		✔			✔
	SL 5170/ P-20	✔						
HIPS	P-20 Steel	✔	✔	✔	✔	✔	✔	✔
	Sintered ST-100	✔			✔		✔	✔
	SL 5170/ P-20	✔		✔				

Table 7: Results from the designed experiment indicating the factors that had a significant effect on ejection force. Interaction effects are shown on the right side of the table.

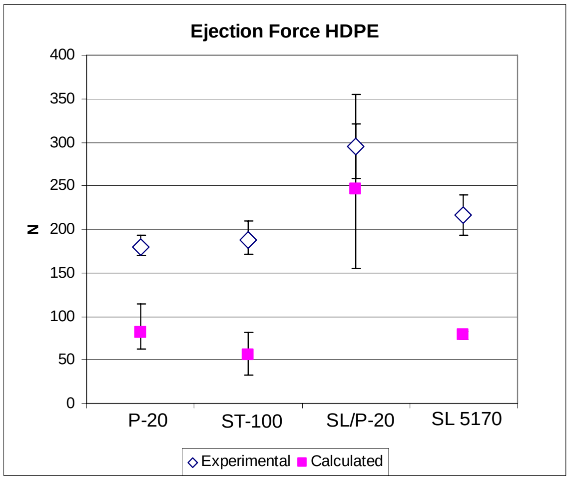


Figure 10: Calculated values for ejection force for HPDE using the model compared with experimental values, averaged across all runs.

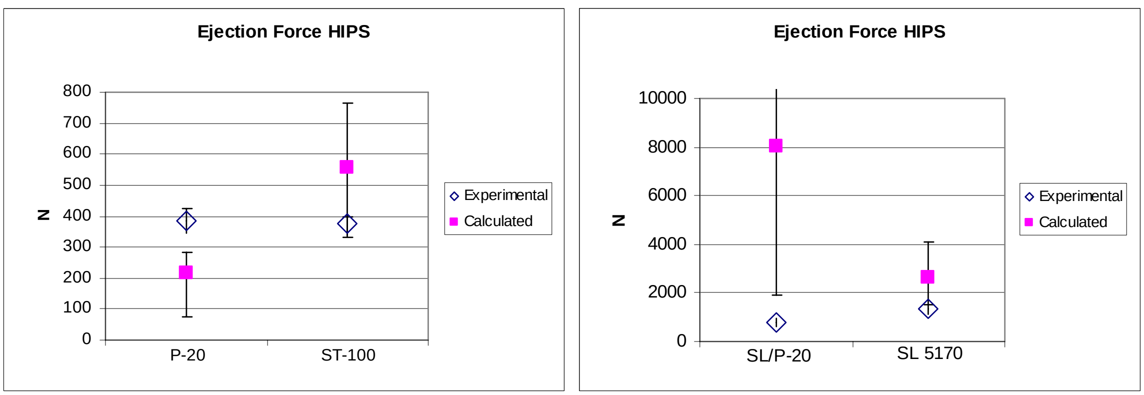


Figure 11: Calculated values for ejection force for HIPS parts from the P-20 and ST-100 cores (left) and the SL 5170 core (right) compared with experimental values, averaged across all runs.

- Varied injection molding process parameters due to materials used
- HDPE parts from P-20 and ST-100 cores flared due to ejection force and material softness
- SL 5170 core susceptible to swelling
- SL 5170 cavity tapered slightly to facilitate ejection
- Surface roughnesses varied among insert cores
- Length of part not measured at time of ejection
- Friction and modulus test environments differed from injection molding experiments
- Elastic modulus of the HIPS more sensitive to temperature than HDPE
- Digital imaging approach used manual transfer of part from IM machine to camera

Table 8: Data reliability issues and possible sources of error.

The friction based model may potentially be applied for predicting ejection forces for new tooling materials. Results from the model were on the same order of magnitude as experimental results. However, the data indicate that the model still needs refinement before it can be a useful tool for such predictions. For example, the ejection force curve in Figure 7 and the results in Figure 9 suggest that there may be some adhesive bonding between the mold and the part that is not accurately accounted for by using friction alone.

For the scope of this work, no limitations of the Laserform ST-100 insert were noted. The capabilities of the SL 5170 injection mold insert, however, were limited because deformation occurred with high pressure, and the material swelled at high temperature. The SL 5170 core did not fail catastrophically during these experiments, but visible defects developed in the core. Therefore it was assumed that the fatigue life would be limited. Adhesion also occurred between the core and the part, which can accelerate failure of the core and affect the part quality. Some unexpected observations of the SL 5170 insert, however, were its general ability to mold both HDPE and HIPS materials and its durability for processing 105 parts.

Conclusions from this experimental research are summarized as follows:

- ST-100 inserts can be used to mold HDPE parts. This insert material performed similarly to P-20, but was affected differently by process parameters. Calculations of apparent coefficient of static friction indicated that friction can be high when packing time is low, but these values did not cause extremely large ejection forces.

- ST-100 inserts can be used to mold HIPS parts. ST-100 performed similarly to P-20, and in some cases had lower ejection forces.

- SL 5170 was used to mold 50 HDPE parts, but with significant deformation in the cavity. This deformation may be minimized by adjusting process parameters and using an alternative cavity material. Ejection temperatures should be relatively high to minimize shrinkage and, thus, the load on the core. Minimizing this load may extend the life of the core prior to the formation of defects.

- SL 5170 is not recommended for molding HIPS due to adhesion and very high ejection forces. The coefficient of friction increased with higher ejection temperatures and packing times due to adhesion, which may have been enhanced by the secondary forces between the two materials. Maintaining a lower ejection temperature (by using a P-20 core) reduced the ejection forces somewhat. Core life, however, would probably have been minimal.

References

1. Kinsella, M.E. 2004, *Ejection Forces and Static Friction Coefficients for Rapid Tooled Injection Mold Inserts*, PhD thesis, The Ohio State University.

2. 3D Systems. 2001, *LaserForm ST-100 Material Typical Properties*, [Online], 3D Systems, Inc., Available from: http://www.3dsystems.com/products/datafiles/lasersintering/datasheets/LaserForm_ST_100_uk.pdf [11 Feb 2005]

3. RenShape® Solutions. 2003, Stereolithography Materials RenShape™ SL 5170, [Online], Vantico A&T US, Inc., Available from: http://www.prototypesplus.com/sl5170.pdf [11 Feb 05]

4. Benabdallah, S.H. 1993, "Static Shear Strength and Adhesion Friction of Some Thermoplastics," *Polymer Engineering and Science*, vol. 33, no. 9, pp. 543-548.

5. Ferreira, E.C., Neves, N.M., Muschalle, R., Pouzada, A.S. 2001, "Friction Properties of Thermoplastics in Injection Molding," *ANTEC Portugal*, [Online]. Available: www.dep.uminho.pt/NP/2001_03.pdf, [July 2003].

6. Wu, S. 1982, *Polymer Interface and Adhesion*, Marcel Dekker, New York.

7. Burke, C., Malloy, R. 1991, "An Experimental Study of the Ejection Forces Encountered During Injection Molding," *ANTEC 1991*, pp. 1781-1787.

8. Pontes, A.J., Pantani, R., Titomanlio, G., Pouzada, A.S. 2001, "Prediction of Ejection Forces in Tubular Moldings in Amorphous Polymers," *ANTEC*, vol. I, pp. 927-931.

9. Menges, G., Michaeli, W., Mohren, P. 2001, *How to Make Injection Molds*, Hanser Gardner Publications, Munich, Cincinnati.

10. Glanvill, A.B. 1971, *The Plastics Engineer's Data Book*, Machinery Publishing Co. Ltd., The Whitefriars Press Ltd., London, p. 30.

11. Kinsella, M.E., Lilly, B., Gardner, B.E., Jacobs, N.J. 2005, "Experimental Determination of Friction Coefficients between Thermoplastics and Rapid Tooled Injection Mold Materials," *Rapid Prototyping Journal*, vol., 11, no. 3, pp 167-173.